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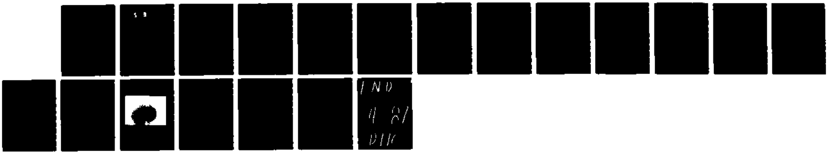

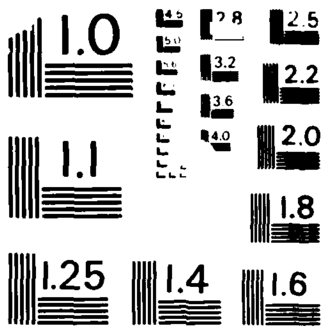

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A summary of progress on the development of instrumentation to determine with great accuracy the in-plane and out-of-plane surface deformations in the vicinity of a crack tip. The purpose is to establish a data base for a) guiding theoretical research in characterizing the deformation fields in the crack tip vicinity for fracture research and b) to provide factual information for the evaluation of currently proposed theories dealing with crack tip deformation. The experimental tools under development are (D. Post's) moire interferometry for the in-plane deformations and optical interferometry for the out-of-plane ones. An essential part of this work is the implementation of a computer-based data processing unit, which is able to record and process in nearly real time fringe patterns into strain fields, and, for known - or estimated - constitutive behavior into stress fields.

This report summarizes the state of developments with particular attention being given

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Cont'd → to the elimination of problems in the vacuum deposition procedure for the metal film used in the moire interferometry. Also, insufficiencies with the optical recording system - insufficient collimation by available lenses - has been rectified. The development of a very efficient code for fringe image recognition by Fourier analysis is discussed.

AFOSR-TR- 87-0259

ANNUAL REPORT ON
AN EXPERIMENTAL AND ANALYTICAL PROGRAM TO DEVELOP
CRACK TIP FRACTURE CRITERIA

by

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1. INTRODUCTION

The fact that a crack exists in a body dominates the nature of the linearly elastic stress distribution near the tip of that crack. This notion of "crack tip autonomy" (with its universal inverse square root of r singularity) has traditionally left only the calculation of the strength of the singularity (Stress Intensity Factor) as the main effort of fracture mechanics research. The stress intensity factor is a function only of the geometry and magnitude of the applied loading, and is independent of material properties.

The stress intensity factor does describe the conditions near the crack tip fairly well for many applications, such as fatigue. However, it has been recognized that the stress response at the tip of the crack must be nonlinear for all but the most brittle of materials. Since the stresses predicted within the linearized theory of elasticity are singular, the material at the crack tip must act in some way to mitigate the effect of the stress singularity through plastic deformation.

There are several analytical models of the nonlinear plasic behavior at the crack tip from the simple Dugdale-Barenblatt cohesive zone model to the power law hardening model of Hutchinson, Rice and Rosengren. Along with high speed computers have come numerous finite element and other numerical approximations. These models make assumptions and predictions about the nature of materials and their fracture response which must be tested under real conditions. Actual displacement, strain and stress distributions must be determined experimentally and compared with the predictions to test the validity of the models. It is also important to determine the extent to which the assumption that the material is a continuum is valid; fracture, at its core, is an inter-atomic process and hence a discrete process. Finite element models attempt to investigate the crack tip region by resorting to smaller and smaller elements, each having the properties of the continuum material, but it is obvious that there is a scale beyond which this discretization cannot be justified.

With these goals in mind, we are attempting to measure with high sensitivity the in-plane as well as the out-of plane displacement field in the region of the crack tip. Once the displacement field is known, the strain field can be calculated from the displacement gradients and the stress field calculated from an assumed constitutive law. These measurements can be used both to validate numerical predictions and as a source for actual

physical input in order to improve the current numerical models. Our measuremens will be performed through Post's method called Moire Interferometry, which optically measures relative in-plane displacements over an entire field. The displacements are revealed as fringes, contours of constant displacement relative to any other point in the field.

Since each measurement will generate an entire field of displacement information, it is necessary to process this data efficiently. A video digitizing system will thus be used to convert the fringe fields into a position-inensity array within a computer. The computer will then convert the fringe information to a position-displacement array, which can be compared with numerical or analytical predictions. The computer can also calculate the displacement gradients numerically and create a position-strain array. With an assumed constitutive law the strains can be converted to stresses.

2. EXPERIMENTAL PROCEDURES

Moire Interferometry is a highly sensitive experimental technique which measures in-plane relative displacements at the surface of a specimen. These displacements are inferred through the change in the diffraction angle of a laser beam as a diffraction grating deforms. The diffraction grating is a high frequency periodic profile variation in a reflective surface. The diffraction angle of the laser beam depends on the wavelength of the grating and, as the grating deforms, the grating wavelength changes and so does the diffraction angle. By using two laser beams from opposite directions, very small changes in the diffraction angles can be detected by looking at the interference fringe pattern between the two diffracted laser beams. In fact, it can be shown that each of the interference fringes corresponds to a contour line of constant relative displacement of the diffraction grating. The displacement increment between adjacent fringes is half the initial (undeformed) wavelength of the diffraction grating. The grating we use has a wave length of about 1.6 microns.

The required diffraction gratings are originally produced on high resolution photographic plates such as those used in holography. A thin coating of aluminum is evaporated onto the surface of the plate to increase the reflectivity. This reflective coating and the grating profile can then be transferred to any flat surface with an epoxy adhesive. We have

produced compact tension fracture specimens in this way, and this method can be used on flat plate specimens of any size and composition. Alternatively, it is possible to apply a photoresist to the specimen itself and produce a grating directly on the specimen in the same way as on a photographic plate. This process should produce a better quality grating, but it limits the size and composition of the specimen since the photoresist must be developed.

It is necessary to hold two laser beams fixed in space for each component of displacement to be measured. We are constructing an interferometer which can measure two independent in-plane displacements simultaneously. As with any interferometric measurement system, vibrations introduce noise to the fringe pattern. We are eliminating this problem by mounting the interferometer and specimen loading device on a vibration isolated optical table.

The interferometer itself uses three laser beams which intersect at the surface of the specimen. Each beam comes from one corner of a square with sides parallel to the specimen. By examining the interference between alternate pairs of intersecting laser beams, three different in-plane displacement components can be measured: 0, 45, and 90 degrees. (Of course one of these components can be derived from the other two.) Each laser beam must originate from the same source and all must travel paths of similar length to the specimen surface in order to get high contrast interference patterns.

Since each fringe represents a contour of constant displacement, as displacement gradients become high, so does the fringe density. this could create a problem, particularly for specimens exhibiting highly plastic deformations. However, with good photographic equipment we expect to be able to resolve 100 fringes/millimeter which corresponds to a strain of about 1% for the grating already described. This is most likely adequate for most metals. However, a coarser grating can allow for higher strain levels, and the displacement sensitivity can be reduced through holographic techniques, if that need arises very close to the crack tip.

At this time the machinery for the production of gratings on holographic plates is in place, as is the vacuum chamber for applying the reflective aluminum coatings. We are able to produce quite good diffraction gratings in this manner. The process of transferring the gratings to a specimen with an adhesive has been tested and seems workable, the major

difficulty being air bubbles in the adhesive causing local faults in the bond. All of the components of the three beam interferometer have been assembled and aligned in a test of the equipment. The table top loading device has been mounted to the optical table and grips are being made to hold the specimens. New specimens will be made in the next month and final alignment of the interferometer can be done at that time. Precise alignment is the most important part of any interferometric measurement system.

At the same time as the in-plane displacements are being measured with Moire interferometry, the out-of-plane displacements can be measured using a Michelson interferometer on the same specimen. The Michelson interferometer compares the surface of the specimen to the surface of a flat mirror; the fringes seen represent contours of constant relative out-of-plane displacement (exactly analogous to the contour lines on a map). The relative displacement between fringes is fixed at half the wavelegth of the laser light used. The Michelson only uses one laser beam at the specimen surface and hence is somewhat simpler to align. The experimental setup we are constructing will allow the measurement of all three displacement components at a specimen surface at the same time during a static test. (Although the surface will have a diffraction grating affixed to it, the height variation of the grating is so small and of such high spatial frequency that it will not be discernible with the Michelson interferometer.)

We expect to have the experimental setup completed and some preliminary photographs of fringe patterns within the next six months. We can then decide if we need to explore alternative specimen geometries or different grating preparation methods. Then we can begin to characterize the displacement fields as a function of load, material properties, and crack geometry.

3. COMPUTER SYSTEM

We have purchased a computer to automate the reduction of the data contained in the interference fringes. The computer itself is a Digital Equipment Corporation LSI 11/73 central processing unit with 4 megabytes (MB) of random access memory and an additional 180 MB of disk storage space. We also have a 70 MB tape cartridge drive for permanent storage.

The fringe patterns are input to the computer system by digitizing a video image. The analog video signal is converted to a digital representation by an Imaging Technology Inc. Analog Processor and sent along the high speed video bus to the Imaging Technology Inc. Frame Buffer where it is stored as an x-y position with a corresponding brightness level. We have the ability to convert a photograph to an array of 1024x960 positions with 256 brightness levels. At this resolution, each picture occupies about one megabyte of memory storage space. This system has been assembled and some basic software to transfer images from the frame buffer to the computer memory and vice versa has been written.

The next work item concerns the development of software to enhance and analyze the fringe patterns. The enhancement consists mainly of filtering out noise and thresholding the image to reduce the fringes to thin black lines on a white background instead a variation of gray levels. Next, a program to trace the position of the fringes with respect to the crack tip will be needed. This part of the process will require some human interaction to impose a coordinate system and to assign a displacement value to each fringe according to the boundary conditions imposed. These programs should also be available to us within the next six months. The displacement field calculated can then be compared to an analytically generated displacement field at each point in the image array.

Calculation of the strain field in two or three dimensions is straight forward in principle once the displacement field is known; however, differentiation can be troublesome as it amplifies non-smooth features in the field. On the other hand, this amplification may indicate regions where continuum assumptions are no longer valid, such as where shear bands occur. By assuming a constitutive law, the stress field may be calculated. We shall first consider classical plasticity theories such as power-law strain hardening models to determine the stress fields. Imposing equilibrium will also help indicate whether the constitutive assumptions are valid.

Although the initial emphasis will be on the two dimensional behavior of the field quantities, we expect to proceed to the study of three dimensional effects in a similar way. These effects depend strongly on the thickness of the specimen as well as the similarity of the crack geometry through the thickness. Numerical calculations allowing for three dimensional effects are also being undertaken.

4. RECENT ACTIVITIES

4.1. Experimental Measurements.

The experimental technique of Moire Interferometry requires a diffraction grating of good quality to be affixed to the surface of the experimental specimen; one indication of the quality of the diffraction grating is the reflectivity of its surface. A highly reflective surface increases the efficiency of diffraction by reducing the amount of light absorbed by the surface. This coating must be thin so that it follows the rippled surface of the diffraction grating exactly and does not significantly alter the structure of the specimen and change the stress and strain fields appreciably. Vacuum coating of aluminum meets these criteria quite well, creating a reflective coating about 5 microns thick, and dedicatedly following the surface contours.

Much of our time recently was spent refurbishing our vacuum coating chamber. In a vacuum, it is possible to cause evaporation of even very dense liquids, such as molten metals. The metal is heated in a small cup, commonly called a boat, and as the metal evaporates, the free molecules fly off randomly into the volume above the boat. When the metal molecules strike a cool surface they adhere, forming a coating which has a thickness which varies inversely with the distance from the boat. In our case, we are using a thin coating of aluminum to improve the reflectivity of our specimens. In order to evaporate aluminum, it is necessary to reduce the pressure in the chamer to about 0.67 millipascals (normal atmospheric pressure is about 101.33 kilopascals, so this is about 6 billionth of an atmosphere). Our vacuum chamber uses two pumps in series to achieve such a vacuum, one of which is a mechanical pump, the other a diffusion pump. A diffusion pump acts by injecting a hot stream of fluid into the line leading to the mechanical pump. The fluid transfers momentum to any molecules of gas it encounters, causing the mechanical pump to see a higher pressure at its intake. The fluid is cooled before it can reach the mechanical pump, and so can be recycled. There were two basic problems with the vacuum chamber which needed correcting. The first problem was that the gauges were not reading reliably, and the second was that the diffusion pump needed cleaning and new fluid. Since the most common problem with any vacuum system is leakage, it was first necessary to ensure that the gauge readings did not indicate leakage of an amount greater than the capacity of the pumps to overcome. Once we were convinced that the system was

reasonably leak-proof we could consider less likely sources of error such as malfunctions of the pumps or gauges. We are convinced that any problems with the coating chamber have been solved and the chamber is ready for use.

Unfortunately, there has been a small setback in our experimental setup. The lens purchased for collimating the laser beam was not as good as had been promised, and has been returned for replacement. A collimated laser beam is a beam that consists of plane waves (or parallel rays), and a nearly collimated laser beam is important both in Moire and Michelson interferometer setups. Perfect collimation is not strictly necessary (and not really possible), since light waves having curvature will also interfere with each other, but the creation of the diffraction gratings used in Moire inteferometry depends on a well collimated laser beam to produce highly parallel grooves in the photoresist with smoothly changing amplitude variations. Also, the reduction of the displacement data contained in a Moire interferogram is based on the assumption that the incoming laser wavefronts closely approximate plane waves which are transformed by the diffraction grating into locally plane outgoing waves. In a Michelson Interferometer, the assumption of a plane wave can be discarded if the path lengths between the laser and the specimen and between the laser and the reference mirror are exactly the same. However, if the laser wavefronts closely approximate plane waves, this requirement of identical path lengths can be relaxed somewhat. There is a second reason for trying to match the path lengths of an interferometer: The coherence length of the laser itself. The output of a laser is very nearly monochromatic (light of a single wavelength), but it does vary slightly with time. A simple model of the output of a laser is the superposition of two light waves having different wavelengths. At certain times the waves will be in phase, while at a later time the waves will be out of phase, so the amplitude and wavelength of the laser output will vary periodically in time. This also means that any instant, the light along the laser beam will vary periodically in space as well. The wavelength of this variation is called the coherence length of the laser, since the light is coherent (having the same wavelength) at integer multiples of this distance. In matching the path lengths of an interferometer it is important that the mismatch in path lenghts be very small compared to the coherence length of the laser used. For a Helium-Neon laser (laser light wavelength = 632.8 nm) the coherence length is about 6 cm. The concept of the coherence length also explains why the light must come from a single source, since matching the outputs of two different lasers would

mean matching exactly the variation and phase of the light waves being emitted by the two lasers. We do have other lenses available to use as collimators, but they will require some redesign of the experimental apparatus.

5. COMPUTER SYSTEM

We have been making more rapid progress integrating our digital image processor (which will be used to automate the reduction of the data contained in the fringe pictures) into our experimental analysis system. Our stand-alone computer has been tied into the campus computer network, which will increase our computing speed as well as allow us access to other hardware and software which is already available on campus and which we can use with little or no modification such as Fast Fourier Analysis routines. Some routines for data reduction have been written. These routines currently rely on dividing the picture into smaller regions in which the fringes follow a consistent pattern. By using that pattern, the computer can calculate the displacement field in each small region and then match the displacements along the boundaries between the regions. It may be possible to completely automate this process, but it is currently much simpler for a human operator to tell the computer what rules to follow in various regions of the picture. This is in effect telling the computer what boundary conditions to use in each region, after which the computer can use the assumption that the fringes imply a continuous and smooth displacement field. In both Michelson and Moire interferometry there is a global ambiguity in the sense of the displacement being measured. For instance, the change in path length in Michelson interferometry may be either positive or negative, but a knowledge of the applied boundary conditions and the expected deformation behavior removes that ambiguity. Once the global sense of the displacement field is estalished, the assumption that the displacements are smooth and continuous allows calculation of the displacement field from the fringes without ambiguity.

One other means of analysis which shows promise is using a Fourier series representation of the images to filter out noise and subtract analytical approximations of the field quantities. One interesting way of approaching this technique is by recognizing that optical transformations (such as imaging through a lens) can be described in terms of Fourier transformations. This means that we should be able to take a fringe picture, pass it

through a lens which would transform the image into a spatial frequency representation, and then by using a suitable mask, filter out the unwanted high and low frequency noise. Such a mask would consist of simple concentric circle apertures whose dimensions would depend on what plane the filter was to be placed in relation to the lens. By then passing the masked image through a second lens, we would invert the Fourier transform and regain the filtered original. Similarly, by constructing a mask which represents the Fourier transform of an analytical approximation, we could remove that approximation from the field and would be left with only the residual prolem to solve.

6. FIGURES

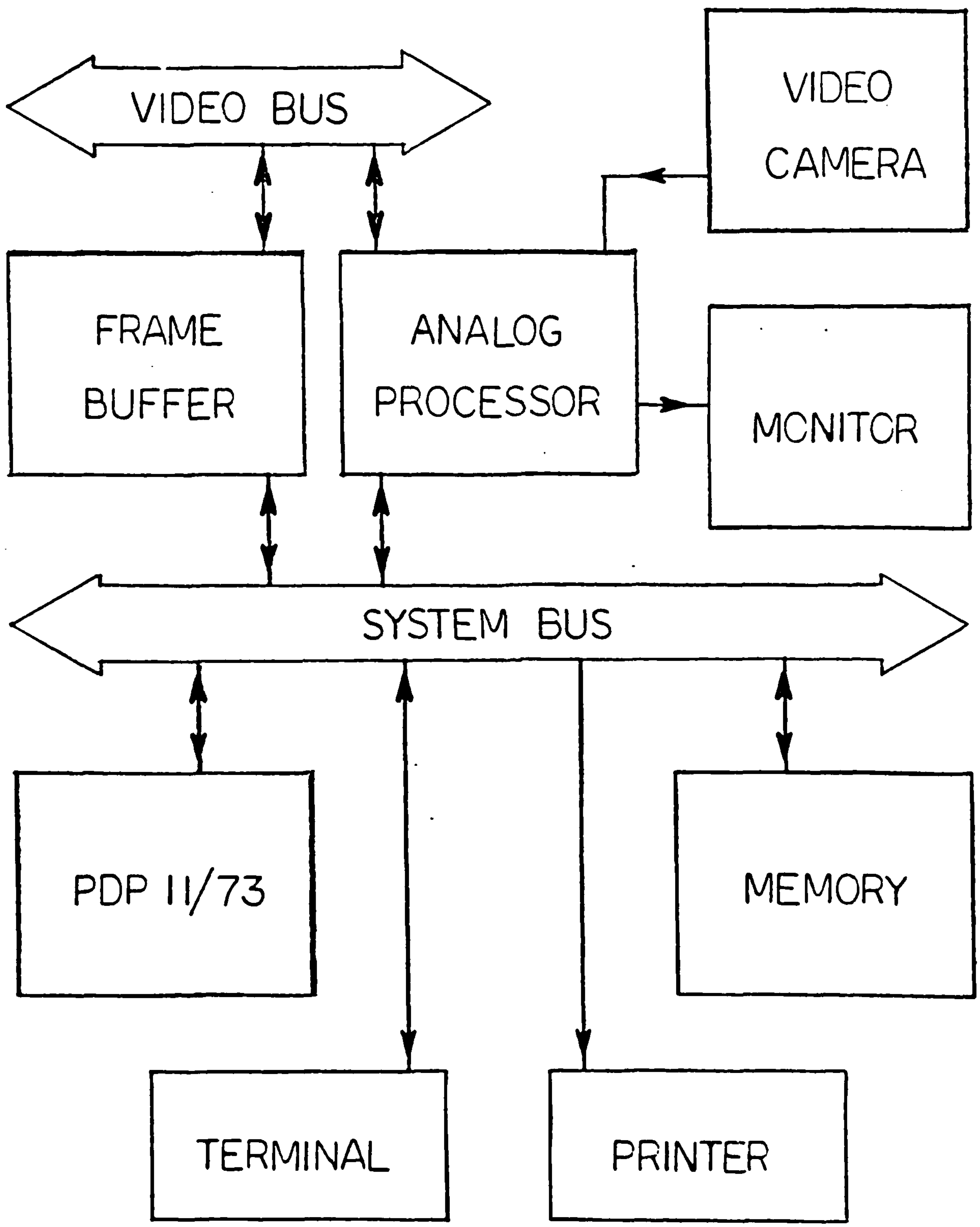
Figure 1 is a diagram of the computer system showing the component parts. The Analog Processor digitizes the television signal and stores the image in the Frame Buffer as an x-y position array of intensity values. These images can then be stored in memory or manipulated using the LSI 11/73 CPU.

Figure 2 is a photograph of the fringes generated using a Michelson interferometer to investigate the out-of-plane displacement of a cracked compact tension specimen under static loading. The crack is shown vertically in the picture with the crack tip in the middle of the picture. The line drawn in the picture represents the approximate location of the intensity trace shown in Figure 3.

Figure 3 shows the light intensity distribution across the picture of Figure 2 as digitized by the computer system. The picture is digitized at 512 horizontal positions with 255 gray levels.

Figure 4 shows the data trace in Figure 3 after filtering to remove the high and low frequency noise in the data.

Figure 5 shows the normalized displacement calculated from the data trace of Figure 4.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VIDEO
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PROCESSOR
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SYSTEM BUS
PDP 11/73
MEMORY
TERMINAL
PRINTER

Figure 1.

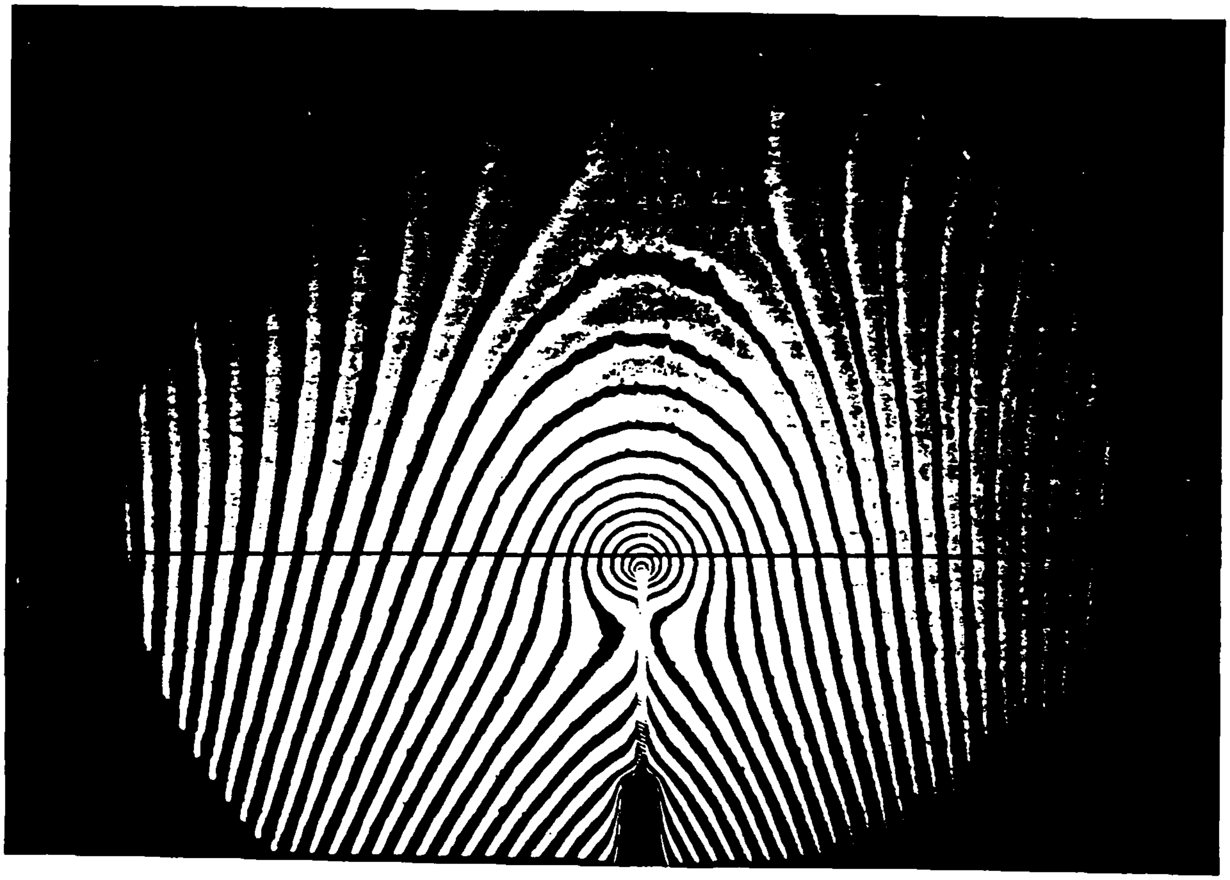
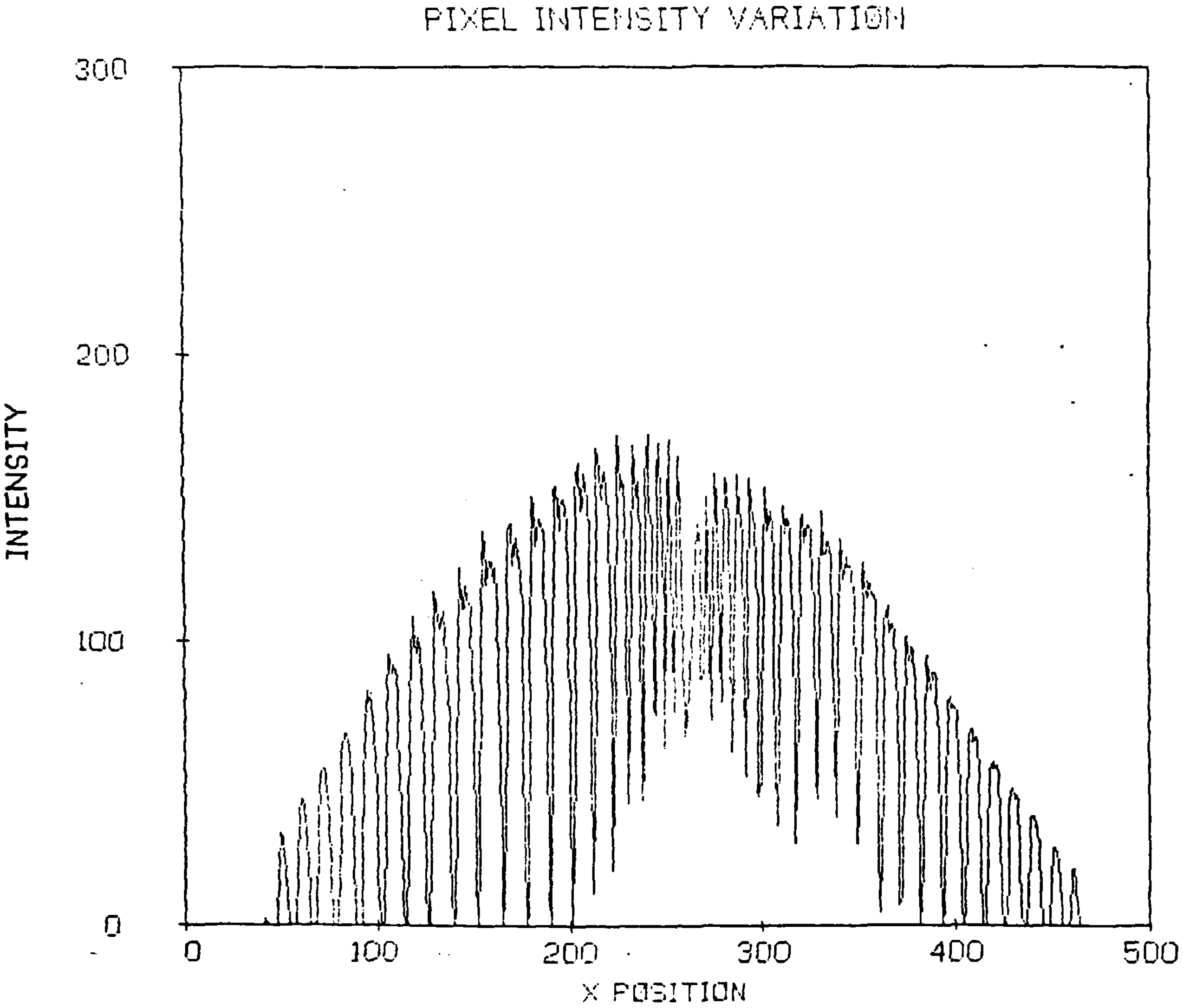


Figure 2.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100
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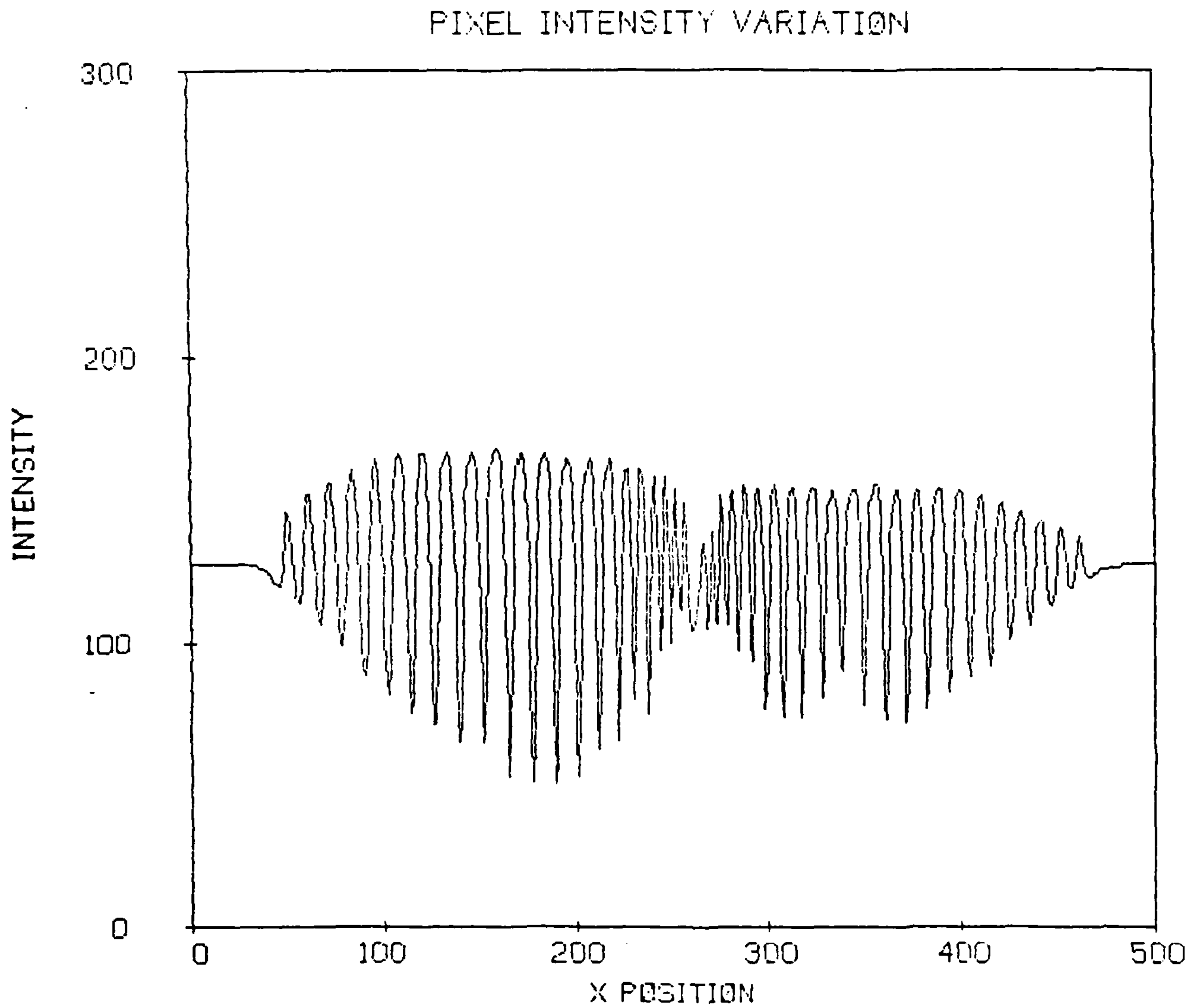
INTENSITY
0
100
200
300
400
500
X POSITION

Figure 3.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INTENSITY
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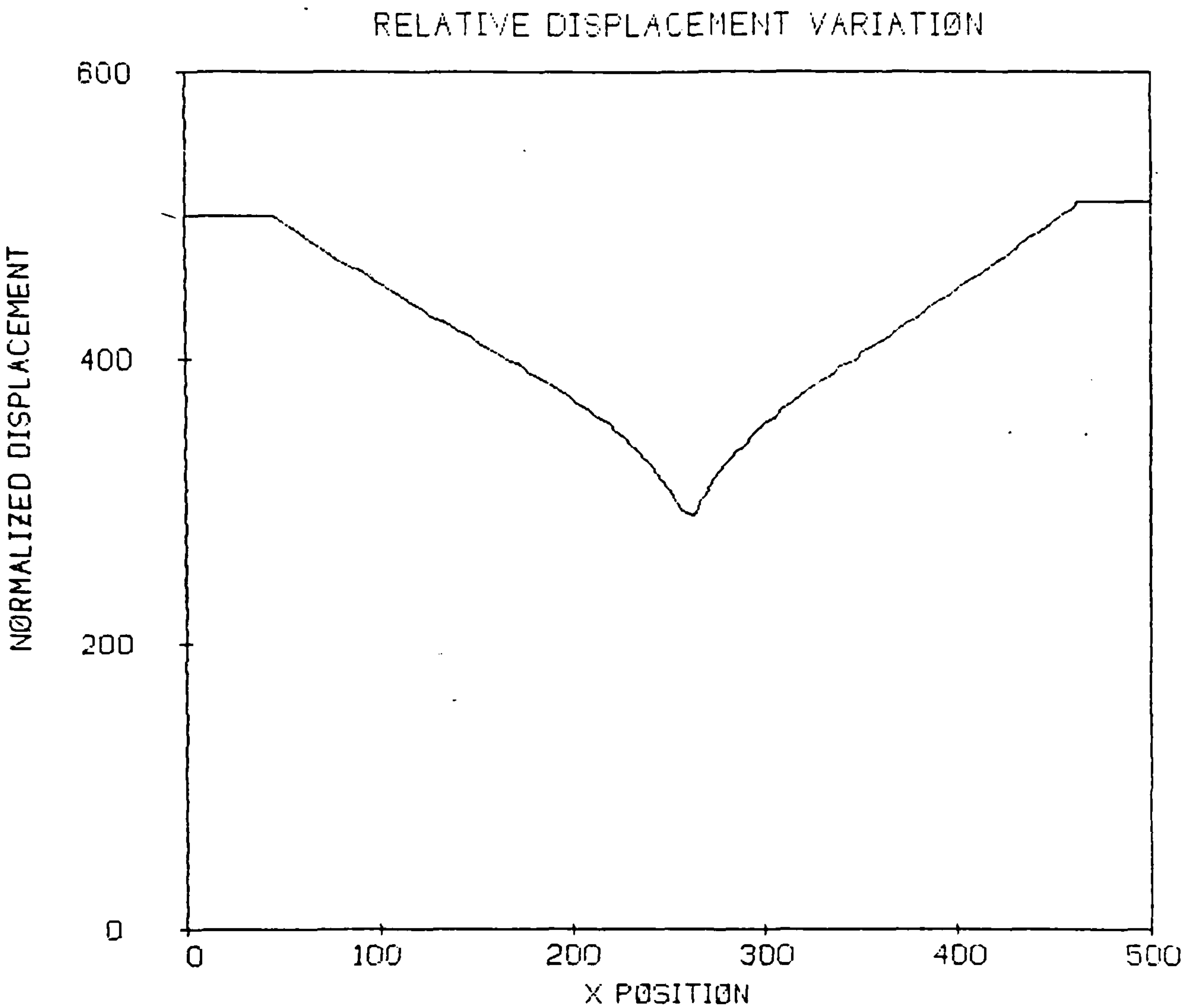
X POSITION

Figure 4.


RELATIVE DISPLACEMENT VARIATION
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400
200
0
NORMALIZED DISPLACEMENT
0
100
200
300
400
500
X POSITION

Figure 5.

END

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